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Fossil Fuel to Solar Power: A Sustainable Technical Design for Street Lighting in Fugar City, Nigeria

Nallapaneni Manoj Kumar[a,] *, Anup Kumar Singh[b], and K. Vinay Kumar Reddy[c]

[a,b,c] *Department of Electrical & Electronics Engineering, Bharat Institute of Engineering & Technology, Mangalpally, Ibrahimpatnam, Ranga Reddy-501 510, Telangana State, India*

Abstract

This paper presents a study on replacing the usage of fossil fuel energy with solar energy for lighting the dark and depressing streets of Fugar city, Nigeria. Fugar city is quite populated area without any street lights, almost every house use fossil energy to light up the streets which they access. The main objective is to select best solution among diesel generators, grid electricity, on-site solar photovoltaics and off-site solar photovoltaics. In order to have a sustainable solution for lighting up 210 LED street lights, the four proposed solutions were analyzed based on their technical feasibility, environmental parameters like CO2 emission analysis and cost analysis with simple payback periods. Analysis showed that, on-site solar photovoltaics is best among the other three proposed solutions in terms of technical and financial feasibility with almost negligible emissions leading to sustainability.

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Keywords: Fossil fuels; Diesel generators; solar energy; on-site solar photovoltaics; off-site solar photovoltaics; LED street lights

1. Introduction

Energy, one of the most important needs of human life. It helps in achieving social welfare and economic development among the nations. Most of the countries depends on fossil fuels for their energy needs. Considering

* Corresponding author. Tel.: +91 94919 25258;
E-mail address: nallapanenichow@gmail.com, nmanoj@biet.ac.in.

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the scenario of Nigeria, which is abundantly blessed with fossil fuels but still facing the problems related power stability and power outages. 'Electricity generation in Nigeria was first dated to 1896, however Nigerian Electricity Supply Company had established in 1929'[1]. O. I. Okoro et al. (2007), had presented a study on the challenges facing by Nigerian power sector. These challenges includes lack of sophisticated technology, political support, financial instability and other environmental problems[2]. A. U. Adoghe et al. (2009), had mentioned in his studies about the complete failure of power sector in Nigeria and the power sector reforms under National Council on Privatization with a motto to improve reliability and stability in supplying power to people[3]. Even after the privatization of energy sector, there were many issues that lead to the decline in power generation levels[4]. Because of this, power outages used to occur frequently. A study conducted by Arobieke Oluwole et al. (2012), had clearly described the power outages in Nigeria, expressing the scenario of not having power for few days even in cities. Few suggestions were made to use an efficient power transmission system to overcome these power outages. Apart from this, use of alternative energy is also suggested[5]. Oyem et al. (2013), analyzed the Nigerian power generation sustainability and pointed out problems related to energy conservation practices that were not followed at the time of power generation. Because of this, Nigerian power sector is unable to supply energy as per the demand levels[6]. To meet the required demand, country has to adopt policies to use alternative energies. Studies conducted by A. S. Sambo (2005), Uzoma. C. C. et al. (2011), C. O. Osueke et al. (2011), and C. N. Ezugwu (2015) on the renewable energy resources availability in Nigeria, shows the best potential for using alternative energies[7-10]. Hence the use of these sources will reduces the power problems to some extent.

Alternative energy generation is easy and the design of implementing such projects is not difficult as fossil fuel power generation projects. For the design of alternative energy projects, there are many softwares which were developed[11] in recent years as per Dinesh Kumar Sharma et al. (2014). In a study by K. Karakoulidis et al. (2011), HOMER based hybrid energy utilization concept is studied for Kavala town, Greece with best combination of PV, Diesel, Battery and Fuel cells and suggested the use alternative energy systems[12]. Ike Chinelo U. et al. (2013), suggested the use of solar powered security lightings for the hostels in Nnamdi Azikiwe University, Nigeria[13]. Mahmoud Wahba (2015), proposed PV power generation for pumping water for the region of El-Kharga Oasis to serve the municipal water needs of the people, Suggestions were made that the PV system is technically and economically feasible[14]. Orville Damaso Cota et al. (2015), suggested the use of solar energy for street lighting and water pumping for the rural communities of Nigeria, especially for Igbelaba village and Jigawa[15]. Mevin Chandel et al. (2014), proposed solar solution for the garment zone in Jaipur City[16], suggestions were made to use solar energy, and apart from this he compared the techno-economic analysis of both off-site and on-site solar power plants. However from the literature study it was clear that solar energy is one of the best solution to meet the energy demand to certain levels considering the distributed generation.

In this paper, four different solutions like Diesel generators, Grid Electricity, On-site solar and Off-site solar were proposed for street lighting in Fugar City. A comparative study is done to choose the best solution among the proposed four solutions in all aspects of technical feasibility, financial feasibility, and environmental impacts etc.

2. Description of the Project Location

2.1. Project location

Fugar is a city in Nigeria located at an altitude of 152 m form the sea level on latitude 7.0833333°, longitude 6.5°, in the northern part of Edo State and it is the headquarters of Etsako Central Local Government[17]. For the welfare of people, local government has initiated LED street light project and this project almost covers the major areas in Fugar City with the total numbers of street lights of 210 each having a capacity of 120 W LED lights. Fugar City map is shown in Fig. 1. Indicates the project layout.

2.2. Solar radiation data in Fugar City, Nigeria

Solar energy utilization project should always be developed after having a thorough knowledge on the solar radiation conditions at the project location. Nigeria is abundantly blessed with solar energy potential of 2,783,723,951 MWh/year as per the NREL data[18]. In this paper, solar radiation data of the location is studied shown in Table. 5. as well in Fig. 3. (Refer to Appendix. A), which was taken from the NASA GEOS-4 model elevation, NASA Surface Meteorology and Solar Energy: HOMER Data[19] for Fugar City with latitude 7.0833333° & longitude 6.5°.

Fig. 1. Project location under study: Black thick lines indicating the street light project layout[17]

2.3. Energy demand

As per the survey conducted, it is concluded that, the main streets of Fugar City needs 210 street lights with 120 W capacity each, mounted on 6 meters height pole and distance between each pole is 25 meters apart. With this capacity the average lumens is 35 LUX and illuminated area would be around 25 m*10 m. The total power demand is the product of each light wattage to the number of lights i.e. 25. 2 kW per day. The time of operation or usage of the load i.e. 25.2 kW would be 12 hrs. Now the energy demand is around 302. 4 kWh per day.

3. Methodology

A survey based studies were conducted in Fugar City, to implement street lighting solution for the social welfare of people. These studies involves the detailed analysis of using fossil fuel energy, grid electricity and the solar power. Hence four different lighting solutions were proposed:

- LED Street lights powered by diesel generator,
- LED streets lights powered by grid electricity,
- On-site solar powered LED street lights, and
- Off-site solar powered LED street lights.

However, the objective of this paper is to select one of the best solution among the proposed solutions by comparing all the feasibilities in terms of Technical feasibility, financial feasibility and environmental impact analysis (mainly CO_2 emissions).

3.1. LED street lights powered by diesel generator

Diesel generator is one of the proposed solutions here, Generator sizing is done as per the specifications of LED light shown in Table. 1. Here 3 single phase generators (for every 70 street lights, one single phase generator of 13 kW is connected) each of 13 kW[20] capacity used for supplying power to 210 street lights.
Generator sizing is as follows: [21-23]

$$KVA\ of\ Generator = \frac{Voltage \times Current}{1000} \tag{1}$$

$$= \frac{230\ V * 42\ A}{1000} = 9.66\ KVA$$

Considering the power factor i.e. 0.95 and efficiency i.e. 93 % of the LED light driver, the required generator capacity is 9.86 kW. As per the generator sizing calculations, its rating should be higher than 9.86 k W. Hence a 13 kW single phase diesel generator is selected for every 70 street lights. 3 generators of each having a capacity of 13 kW is required.

Table 1. Generator sizing specifications[20, 24]

Product name	Parameter	Rating with units
LED Light Model: CSL-B120 (CREE XTE LED)	Power	120 Watts
	Input voltage	24 V DC
Driver Model: MEAN WELL-HLG-120 H-24	DC output voltage	24 V DC
	Rated output current	5 Amps
	AC input voltage	230 V
	Input current	0.6 Amps
	Frequency range	47 ~ 63 Hz
Single Phase Diesel Generator: Cummins-Model No. 13.0GSBA6712/22, SKU CURE-013T001	Maximum Output	13 kW
	Continuous Output	11.2 kW
	Continuous Load Amperage (Amps) at 240 V	47 Amps

3.2. LED street lights powered by grid electricity

Apart from the diesel generator, another proposed solution is the use of grid electricity from a nearest transformer. For this kind of solution, the LED lights required are different form the normal solar LED lights. The only difference between these two lights is input supply and the drivers used for their operation. However the power rating and energy consumed is similar for both the types. Power required to operate 210 LED street lights is 25.2 kW. Energy consumed by these 210 street lights to operate for 12 hr. is 302.4 kWh/day.

3 phase supply is taken and the load is balanced by connecting 70 street lights to each phase. Even though load is balanced there is huge flickering in the last 20-30 lights in each phase. This is because of the low current. Apart from this, a problem of power outages on an average 12-16 hr. in a day and instability in the power supply from the grid side in Nigeria[4, 5].

3.3. On-site solar powered LED street lights

In on-site solar powered LED Street lights, see in Fig. 2. Photovoltaic panels are mounted on the top of a pole, batteries and other controllers are equipped in a box and this is either mounted on the pole or buried under the ground. Design calculations for one on-site solar powered LED Street light is considered because the rating and size of other 209 street lights are similar, See Table.2. for the on-site solar powered LED street lighting system project specifications. Design methodology for designing a solar street light is as follows: The power required for the light to be operated is 120 W, considering the losses in the system[16, 25] power is multiplied by 1.3 times to get the actual power i.e., 156 W. The peak energy required to be produced by the photovoltaic panel for the operation of the LED light for 12 hours in the night in a day is 1872 Wh/day. While designing solar power utilization system, it is essential to consider panel generation factor (PGF) [16, 25], which is calculated as per the location solar resource data. As per the solar resource data tabulated in Table.5 (Refer to Appendix. A), the maximum possible solar irradiance for the fugar city is 5.84 k Wh/day.

PGF= (Solar Irradiance × Sunshine Hours)/ (Standard Testing Condition Irradiance) (2)

Panel Generation Factor (PGF) = 5840/1000= 5.84 (3)

Peak energy required on the daily basis is 1872 Wh/day. Now the total watt required from the photovoltaic panel (PV) is:

Watt from PV Module = (Peak Energy Required)/PGF (4)
= 1872/5.84 = 320.55 W

Number of photovoltaic modules or panels required to produce 367.77 W is given as the ratio to the power required by the modules to the rated power of a single module, refer to Table. 2 for the specifications of the module:

No.of PV Modules=320.55/160= ~ 2 Modules (5)

Battery is required to store energy, i.e. produced by the PV modules in the day time. No. of batteries required are calculated as follows by considering its depth of discharge (DOD) i.e. 0.6 and the losses in the battery i.e. 15 %[16, 26].

Battery Capacity = (Wh/day × Days of Autonomy)/ (η × DOD × System Voltage) (6)
= (1440×1)/ (0.85×0.6×24) = 117.64 Ah

No.of Batteries = (Battery Capacity)/ (Rated Capacity of the Battery) (7)
= 117.64/200 = 0.58 i.e., ~ 1 Battery

After the battery sizing, it is clear that the system requires 1 battery but however the system voltage is different from the nominal voltage of the battery, to get the required system voltage as 24 V, two batteries are connected in series. Hence two batteries are required for storing energy from PV system.

Charge controller is selected based on the current value of the PV array. Charge controller rating should be 1.3 times of the short circuit current of the PV array[25]. PV array short circuit current is 9.82 A, charge controller current rating should be more than 12.76 A. Hence 20 A/24 V Phocos industrial charge controller[27] is selected.

Table 2. On-site solar street light project specifications[24]

Product Name	Parameter	Rating with Units
LED Light Model: CSL-B120 (CREE XTE LED)	Power Input Voltage	120 W 24 V DC
PV Panel: JS 160	V_{OC} I_{SC} P_{MAX} V_{MAX} I_{MAX} Efficiency	22.25 V 9.82 A 160 W 17.5 V 9.14 A 13.7 %
Battery: NPG12-200	Rated Capacity Nominal Voltage	200 Ah 12 V
Phocos Industrial Charge Controller: CIS XX 2L	Nominal Voltage Maximum Charge/ Load Current	12/24 V 20 A
Street Light Pole	Height of the Pole No. of Street Light	8 meters 210

Note: All the above parameters are nominal

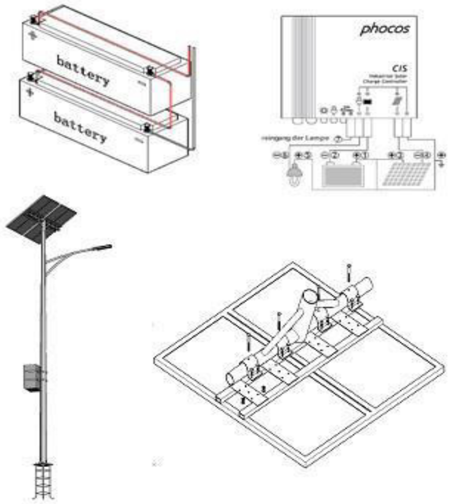

Fig. 2. Schematic view of on-site solar street light[24]

3.4. Off-site solar powered LED street lights

Off-site solar power is the one which is away from the load utilization center. In this, power generated at one place is distributed to the area where exactly it is required. Design procedure is almost similar to that of an on-site solar power generating station, but a DC to AC converter, i.e. inverter should be used extra. Apart from this for installing this kind of power station requires vast land area, off-site solar power generating station is to be designed to power 210 LED streets and its design procedure is as follows and the specifications were tabulated in Table.3:

In both the designs of on-site and off-site, panel generation factor (PGF) is same, i.e. 5.84.

The power required to operate 210 street lights of 120 W each after considering the losses in the system[16, 25] power is multiplied by 1.3 times to get the actual power i.e., 32, 760 W.

Inverter size should be 20-30 % greater than the actual utilization load[16, 25]. Actual load is 25. 2 kW, so inverter should be of 30 % higher capacity, i.e. 32.76 kW. Here a 50 kVA/ 180 V DC inverter[28] is selected for the power station by considering the future load increment.

The peak energy required to be produced by the photovoltaic panel for the operation of the LED lights for 12 hours in the night in a day is 393, 120 Wh/day.

Peak energy required on the daily basis is 393, 120 Wh/day. Now the total watt required from the photovoltaic panel (PV) is:

$$\text{Watt from PV Module} = (\text{Peak Energy Required})/\text{PGF} = 393{,}120/5.84 = 67{,}315.06\ \text{W} \tag{8}$$

Number of photovoltaic modules or panels required to produce 67,315.06 W is given as the ratio to the power required by the modules to the rated power of a single module.

$$\text{No.of PV Modules} = 67{,}315.06\ \text{W}/160\ \text{W} = \sim 421\ \text{Modules} \tag{9}$$

PV array is designed with system voltage specification, i.e. inverter input is 180 V DC. 11 PV modules are connected in series and this is calculated by the ratio of inverter input voltage to the PV module maximum voltage. Total number of PV arrays required is the ratio of total number of modules to that of number modules in series, i.e. 38.27.

Battery is required to store energy, i.e. produced by the PV modules in the day time. No. of batteries required are calculated as follows by considering its depth of discharge (DOD) i.e. 0.6 and the losses in the battery i.e. 15 %[16, 26].

$$\text{Battery Capacity} = (\text{Wh/day} \times \text{Days of Autonomy})/(\eta \times \text{DOD} \times \text{System Voltage}) = (302{,}400\times1)/(0.85\times0.6\times180) = 3{,}294.12\ \text{Ah} \tag{10}$$

$$\text{No.of Batteries} = (\text{Battery Capacity})/(\text{Rated Capacity of the Battery}) = 3294.12/200 = 16.47\ \text{i.e.,} \sim 17\ \text{Battery} \tag{11}$$

After the battery sizing, it is clear that the system requires 255 batteries each of 12 V/ 200 Ah, in which 17 branches are connected in parallel with each branch consisting of 15 batteries in series. This is because the system voltage is 180 V DC.

Cable selection is made as per the current ratings. Here each pole requires 25 meters of cable to connect from the main line. Main line underground cable is also selected based on the current ratings. Here the installation of cables is done fully underground.

Table 3. Off-site solar street light project specificationS[24, 28]

Product Name	Qty.	Parameter	Rating with Units
LED Light Model: CSL-B120	210	Power	120 W
(CREE XTE LED)		Input Voltage	24 V DC
PV Panel: JS 160	421	V_{OC}	22.25 V
		I_{SC}	9.82 A
		P_{MAX}	160 W
		V_{MAX}	17.5 V
		I_{MAX}	9.14 A
		Efficiency	13.7 %
	255	Rated Capacity	
Battery: NPG12-200			200 Ah
		Nominal Voltage	12 V
Xantra inverter with integrated charger	1	Input DC Voltage	180 V DC
		Inverter kVA Rating	50 kVA
Street Light Pole	210	Height of the Pole	8 meters

4. Results and Discussion

The above proposed solutions were analyzed in different aspects like technical feasibility, cost analysis and the environmental impacts. These three analysis were done to choose the best solution among the proposed solutions, see Table.4.

4.1. Technical Feasibility

Diesel generators are technically feasible at any location. These generators supply a constant output as long as it works. Grid electricity is also technically feasible in most of the countries but in Nigeria, it is quite unstable with huge power outages. This may even lead to the failure of the lighting systems because of low currents and continuous flickering. So grid electricity is not technically feasible for this application. Another proposed solution is solar energy, which is the most promising solution for meeting the energy needs of many countries. As long as the sun shines, we can harvest solar energy more effectively using PV modules and other power electronic conversion techniques. Hence solar energy is technically feasible.

4.2. Emission analysis

Present day world is looking for efficient technologies, with almost negligible levels of emissions. So in this study all the proposed solutions were analyzed, on the basis of emitting CO2 emissions. CO2 emission for grid electricity is the product of emission factor for grid electricity to the amount of energy consumed in kWh[29]. The emission factor for grid electricity in Nigeria is 0.43 kg CO2/kWh[29]. Hence the amount of emission released in to the atmosphere for 302.4 kWh of energy per day is around 132.94 kg CO2 and on annual basis, this emissions would be around 47,858.4 kgCO2/year. Similarly CO2 Emissions released for diesel generators with the consumption of diesel is given as the product of amount of fuel used, its heating value and its emission factor[30]. Heating value and emission factor of diesel is given as 0.0371 GJ/liter and 67.22 kg CO2/GJ[31]. The amount of emissions released on daily basis for burning 55.5 liters of diesel are 138.41 kg CO2/day and on annual basis the amount of emissions released into atmosphere are 49,829.15 kg CO2/year. When it comes to solar, the amount of emissions released are almost negligible. Hence solar photovoltaic system is the most environmental friendly solution among the proposed solutions.

4.3. Cost and payback period analysis

Energy generation is becoming costlier day by day with the advancement in technology and other factors. Here cost of three different energy generation systems is compared with respect to capital cost, operating cost. Shown in Table. 6. (Refer to Appendix. A) Apart from this simple payback periods were also evaluated by considering monthly energy consumption cost for grid electricity. Capital cost (C.C) involved in Diesel generator (D.G) powered LED Street is estimated to be US $ 148,948.58. Capital cost involved in on-site solar photovoltaic powered LED Street light is estimated to be US $ 223,650.00. Similarly the capital cost involved in offsite solar photovoltaic powered LED Street lights is also estimated to be US $ 278,485.70. If the entire 210 street lights are powered using grid electricity, the cost involved is the monthly energy consumption cost as per the Benin electricity distribution company (BEDC) tariff rates.

As per BEDC, the tariff rate for one unit of energy consumption (kWh) is US $ 0.10 (this is only for street lighting purpose)[32]. The average cost for monthly energy consumption would be around US $ 907.20, similarly on an annual basis the total e-bill that is to be paid, is around US $ 10,886.40. When compared to the proposed systems this is much cheaper, but it’s not technically feasible in Nigeria because of stability issues and power outages. Hence one of best option is selected among those three proposed solutions which gives a reliable power supply with less cost for lighting up the darker streets of Fugar. By considering annual energy bills as per BEDC, payback periods were estimated for three proposed energy generation systems as follows: Simple payback period is calculated as the ratio of total cost involved to the setup the power plant to the monthly energy bill savings. Payback periods for Diesel generator units, on-site solar photovoltaic system and off-site photovoltaic system are 13.68 years, 20.54 years and 25.58 years respectively. These payback periods were considered without considering the operating cost. However in solar operated systems operating cost is almost zero and its life time is 25 years[12] but in the diesel generators the operating cost i.e. fuel cost for operating 210 LED street lights for 12 hours in a day is US $ 41.63. Hence, the operating or running cost on annual basis is estimated to be US $ 14,985.00. This estimated running cost of diesel generators units is continued till the life time of generators, if it is considered that the life time of generator is 10 years, then running cost would be estimated as US $ 149,850.00.

When this running cost is added to the capital cost then, the payback periods are almost doubles i.e. 27.44 years, which is not economically feasible. Another disadvantages of using diesel generators are of huge noise and environmental pollution. Now when on-site solar is considered and whose payback periods are 20.54 years, this helps in saving e-bills for the duration of another 4.46 years (as solar PV systems life span is 25 years) i.e. is around US $ 48.553.34., which can be used for maintenance of the system during failures. Hence in the above proposed solutions, On-site solar powered LED street lighting system is technically feasible as well financially viable.

Table 4. Comparison of the proposed solutions based technical feasibility, financial viability and CO_2 emission levels.

Proposed Solution	Technically Feasible (YES/NO)	Financially Viable (YES/NO)	Environmentally Friendly (CO_2 Emissions) (YES/NO)
Diesel generator powered LED street lights	YES	NO	NO
LED street lights powered by Grid Electricity	NO (Stability & Power outage issues)	YES	NO
On-site solar powered LED street lights	**YES**	**YES**	**YES**
Off-site solar powered LED street lights	YES	NO	YES

4. Conclusion

A sustainable technically feasible solution for lighting the darker streets of Fugar city is studied here. The results showed, on-site solar powered LED street lighting system is technically, economically feasible and environmentally friendly than the diesel generators responsible for noise and environmental pollutions, grid electricity which is not stable and reliable source with power outages, and off-site solar which is technically feasible and environmentally friendly but not feasible in financial point of view.

Future work

Future work will be on the detailed financial parameter analysis and reliability analysis.

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Appendix A.

Table 5. Monthly average solar radiation on a Horizontal surface (kwh/m^2/day) in Fugar City, Nigeria[19]

Month	Monthly average solar radiation on a Horizontal surface (kWh/m^2/day)
January	5.77
February	5.84
March	5.71
April	5.42
May	5.13
June	4.70
July	4.34
August	4.13
September	4.33
October	4.80
November	5.40
December	5.59

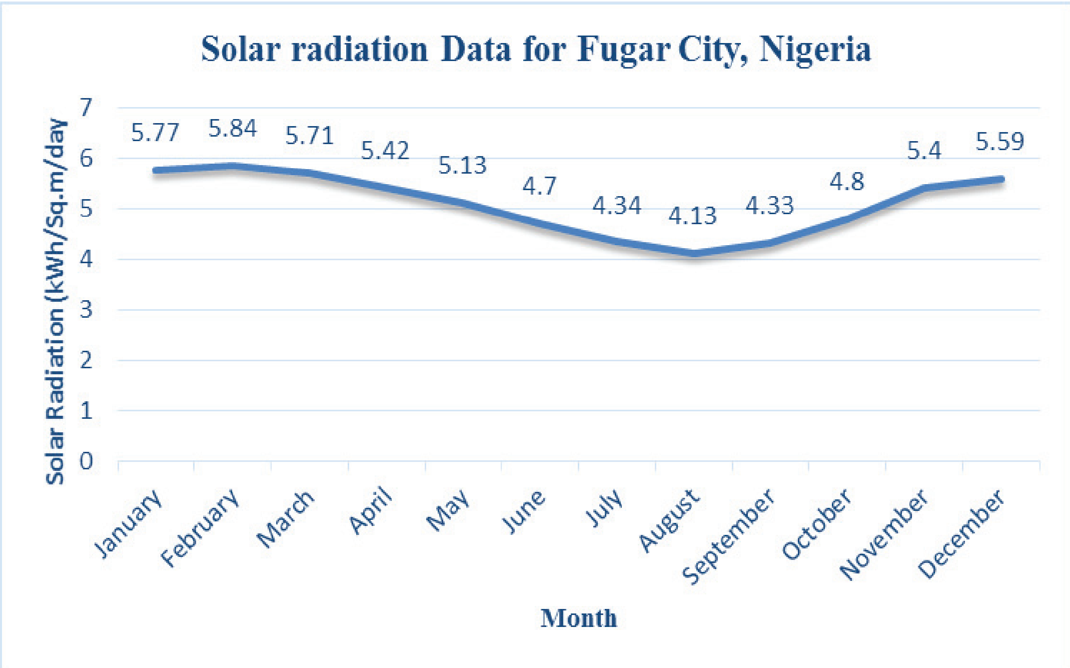

Fig. 3. Monthly average solar radiation on a Horizontal surface (kwh/m^2/day) in Fugar City, Nigeria[19]

Table 6. Estimated Capital cost and Operating Cost for Setting up the Power Generation Solutions for Fugar City, Nigeria

Diesel Generator Unit				On-site Solar Powered LED Street Lighting Unit				Off-site Solar Power Plant			
Module	*Qty.*	*Unit Cost ($))*	*Amount ($)*	*Module*	*Qty.*	*Unit Cost ($)*	*Amount ($)*	*Module*	*Qty.*	*Unit Cost ($)*	*Amount ($)*
13 kW DG	3	6100	18300	PV Module	420	128	53760	PV Module	421	128	53760
120 W LED Light	210	213	44730	Battery	210	198	41580	Battery	255	198	50490
Street light pole	210	300	63000	Charge Controller	210	43	9030	50 kVA Inverter	1	32983	32983
2.5 Sq. mm (3 core)	2100 meters	1.6	3360	120 W LED Light	210	213	44730	120 W LED Light	210	213	44730
25 sq. mm Cable (4 core)	30 meters	5.2	156	Street Light Pole with battery box and panel mounting facility	210	339	71190	Street Light Pole	210	300	63000
16 sq. mm Cable (4 core)	5250 meters	3.6	18900	2.5 Sq. mm (3 core)	2100 meters	1.6	3360	PV Panel Mounting Structure	For 421 Panels	8290	8290
Land Cost			502.58	Land Cost	0.00	0.00	0.00	2.5 Sq. mm (3 core)	2100 meters	1.6	3360
								25 sq. mm Cable (4 core)	90 meters	5.2	468
								16 sq. mm Cable (4 core)	5250 meters	3.6	18900
								Land Cost			2504.70
Capital Cost (C.C)			**148,948.58**	**Capital Cost (C. C)**			**223,650.00**	**Capital Cost (C.C)**			**278,485.70**
Fuel Cost (Diesel Consumption) per day	55.5 Liters	0.75	41.63	Fuel Cost	0.00	0.00	0.00	Fuel Cost	0.00	0.00	0.00
Operating Cost (O.C) (for five years, this is because of its life expectancy)			**74,925.00**	**Operating Cost (O.C) (25 years life expectancy is possible)**			**0**	**Operating Cost (O.C) (25 years life expectancy is possible)**			**0**
Total Cost (C.C +O.C)*			**223,873.58**	**Total Cost (C.C+O.C)***			**223,650.00**	**Total Cost (C.C+O.C)***			**278,485.70**

*Total cost is not inclusive of maintaining cost as well as the failure rates.

NOTE: Cost details as per the present market levels and they are taken from the Atiode solar systems Pvt. Ltd. This might vary in the future.

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